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COMPARISONS OF RESULTS OBTAINED WITH SEVERAL  
PROTON PENETRATION CODES

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## TABLE OF CONTENTS

	<u>Page No.</u>
Abstract -----	1
I. Introduction -----	1
II. General Code Description -----	2
III. Description of Problem -----	3
IV. Results and Conclusions -----	4
Acknowledgments -----	7

COMPARISONS OF RESULTS OBTAINED WITH SEVERAL  
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W. Wayne Scott and R. G. Alsmiller, Jr.

ABSTRACT

Comparisons of the results obtained for a hypothetical problem with four different proton penetration codes included in the Radiation Shielding Information Center's code collection are presented. All the codes include secondary-particle production and transport in some approximation. The hypothetical problem was to find the dose as a function of depth in tissue resulting from a typical solar-flare proton spectrum normally incident on an infinite slab shield which is followed by the slab of tissue. The tissue was assumed to be  $30 \text{ g/cm}^2$  thick. The solar proton spectrum was taken to be exponential in rigidity with a characteristic rigidity,  $P_0$ , of 100 MV and was normalized to  $10^9$  protons/ $\text{cm}^2$  with energy  $> 30 \text{ MeV}$ .

Graphs comparing both the total and the various secondary-particle contributions to the dose for aluminum and iron shields are presented. Definite inconsistencies between some of the codes are apparent.

I. INTRODUCTION

For a number of years, various groups have been developing computer codes to evaluate proton-penetration shielding problems. These codes are all intended to solve the same type of problem but, since they are using different approximations and a variety of input data, they do not necessarily give the same answers to any given problem.

In general, of course, the validity of the calculations can be determined only by comparison with experimental data, but, because of the lack of the required data, such comparisons have not been made. In this report the consistency of the codes with each other is determined by comparing the calculated results of each code to a hypothetical problem. While this type of comparison cannot be used to establish the general validity of any code, it can, perhaps, be used as a guide in deciding between the various codes for doing specific calculations.

The codes considered in this report are NTC,<sup>1</sup> developed by the Neutron Physics Division of Oak Ridge National Laboratory; BPPC,<sup>2</sup> developed by the Nuclear and Space Physics Department,\* Aero-Space Division, The Boeing Company; LPSC,<sup>3</sup> developed by the NASA Lewis Research Center; and LPPC,<sup>4</sup> developed by the Nuclear Analysis Department of the Lockheed-Georgia Company. These codes were chosen for study because they are presently included in the code collection of the Radiation Shielding Information Center<sup>†</sup> and are available to users through the Center.\*\*

In section II the major differences between the codes are briefly discussed. In section III the hypothetical problem is described. The comparisons are given and discussed in section IV.

## II. GENERAL CODE DESCRIPTION

The four proton shield codes calculate the primary- and secondary-particle doses behind multilayer shields of infinite extent and finite thickness due to a prescribed incident flux of protons. Since very detailed descriptions of the codes and the data used in the codes are given in references 1-4, only a few general comments on the main differences between the codes will be presented here.

The nucleon transport code, NTC, employs Monte Carlo methods and is unique among the codes being considered in that the angular distribution of the secondary particles produced by all elastic and nonelastic nuclear collisions is taken into account. LPSC and LPPC use the straightahead approximation in treating the high-energy cascade particles produced from nonelastic nuclear collisions -- that is, it is assumed that when a nonelastic collision occurs the high-energy secondary particles are emitted in the direction of the incident particles. Both LPSC and LPPC

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\* Now called Boeing Space Center and located at Kent, Washington.

† The codes are packaged for distribution as CCC-7/NTC, CCC-76/BPPC, CCC-64/LPSC, and CCC-51/LPPC, respectively.

\*\* The proton-penetration code CHARGE,<sup>5</sup> developed by the Missile and Space Systems Division of Douglas Aircraft Company, Inc., is now included in the RSIC Computer Code collection as CCC-70, but it was not available in time for use in these studies.

assume that the low-energy evaporation secondary neutrons from nonelastic nuclear collisions are emitted isotropically and take into account this angular dependence. BPPC uses the straightahead approximation in treating all secondary particles and also considers only first-generation secondary particles -- that is, it considers only those secondary particles that are produced by incident protons.

NTC and LPSC use data developed by Bertini<sup>6</sup> for particle production from high-energy nonelastic collisions. LPPC and BPPC were developed before the Bertini data became available and rely on the data given by Metropolis et al.<sup>7</sup> The data of Bertini and Metropolis are in reasonable agreement, but, because only a few energies and elements were considered by Metropolis et al.,<sup>7</sup> much extrapolation and interpolation was required to obtain the data which are actually used in the LPPC and the BPPC codes. Therefore, the particle-production data used in these codes may be quite different from those used in the NTC and LPSC codes.

### III. DESCRIPTION OF PROBLEM

The hypothetical problem considered is to find the dose as a function of depth in tissue when a typical solar-flare-proton spectrum is normally incident on a slab of material 20 g/cm<sup>2</sup> thick, which is followed by a slab of tissue 30 g/cm<sup>2</sup> thick. The flare spectrum is taken to be exponential in rigidity, with a characteristic rigidity of 100 MV and is normalized to 10<sup>9</sup> protons/cm<sup>2</sup> with energy greater than 30 MeV; i.e.,

$$J_p(>E) = K e^{\frac{P(30)}{P_0}} e^{-\frac{P(E)}{P_0}}, \quad 50 < E < 400 \text{ MeV},$$

$$P(E) = \frac{1}{e} [E(E + 2M_p)]^{\frac{1}{2}},$$

$$K = 10^9 \text{ protons/cm}^2,$$

$$P_0 = 100 \text{ MV}.$$

Only the portion of this spectrum between 50 and 400 MeV was considered

in the studies reported here. The incident protons below 50 MeV do not get through the shield and therefore will contribute to the dose only by producing secondary particles in the shield. This production is small and is not considered here. The restriction to incident particles of less than 400 MeV arises because of limitations in NTC. The Bertini data<sup>1,6</sup> which are used in NTC are valid only to energies of this order of magnitude.

Calculations and comparisons have been made for shield materials of aluminum and iron. Aluminum is, of course, a typical shield material for spacecraft, and iron is assumed to be indicative of the heavier elements.

In doing the calculations with LPSC, it was necessary to make a slight approximation. The LPSC library does not contain tissue as one of the available shield materials, and therefore it was necessary to replace tissue with water. The error introduced by this approximation is thought to be of little significance to the comparisons considered here.

#### IV. RESULTS AND CONCLUSIONS

In addition to the total dose as a function of depth in tissue, comparisons are given of the primary proton dose, the secondary proton dose, and the secondary neutron dose. A primary proton is defined to be an incident proton which has undergone neither elastic nor nonelastic nuclear collision.

The comparisons are shown in Figs. 1-16, with the appropriate legends describing each.\* The ordinate represents the tissue dose in units of rad or rem, and the abscissa gives the depth in tissue in g/cm<sup>2</sup>. The BPPC results for iron are not shown because this code contains data for aluminum and tissue only. Comparisons in rem are limited to LPSC and NTC because only these codes perform the dose equivalent calculation.

Prior to this investigation, it was anticipated that the results of each code for the primary proton dose shown in Figs. 1-4 would compare favorably. This expectancy is borne out to some extent in that the maximum variation from the mean of the curves is of the order of 20% or

\*The calculations done with NTC were carried out by D. C. Irving, R. G. Alsmiller, Jr., and H. S. Moran and will be reported in detail elsewhere.

less. No attempt has been made to identify the source of this variation but it seems reasonable to assume that it is due to a large extent to differences in the stopping-power data in the various codes.

By comparing the LPSC and NTC curves in Figs. 1 and 2 and in Figs. 3 and 4, one sees that the average proton quality factor in LPSC is somewhat smaller than that in NTC.

The secondary proton doses are shown in Figs. 5-8. In Fig. 5, i.e., in the case of an aluminum shield, the LPSC, LPPC, and NTC curves are in rather good agreement, while the BPPC curve is much lower than the other three over most of the tissue depth. No explanation for this serious disagreement between the BPPC results and those obtained with the other codes has been found. In Fig. 7, i.e., in the case of an iron shield, the LPSC and NTC curves are in reasonable agreement but are quite different from the LPPC curve. A preliminary explanation for this large LPPC result is available. The secondary proton flux per unit energy range given by LPPC (these values are not given in this report) shows an erroneous increase at high energies.\* This increase is also present in the aluminum calculation, but it is not so pronounced as in the iron calculation and does not have a decisive effect on the dose.

In Figs. 6 and 8 the dose in rem calculated with LPSC is smaller than that obtained with NTC. This discrepancy is due at least in part to the fact that the NTC dose includes a contribution from heavy charged particles which have a large quality factor, while these heavy particles are neglected in LPSC.

The secondary neutron doses are shown in Figs. 9-12. In Fig. 9 none of the curves are in good agreement. The BPPC curve is higher than the other three over most of the tissue depth.\*\* At small depths the LPSC

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\* C. W. Hill of the Nuclear Analysis Department, Lockheed-Georgia Company, agrees that this flux is erroneous but he has not as yet isolated the source of the difficulty.

\*\* M. Wilkinson of the Boeing Company Space Center has informed us that he considers the secondary neutron dose shown in Fig. 9 to be too large. By introducing neutron removal cross sections into the BPPC code, he has obtained a secondary neutron dose which is roughly comparable to that given by the other three codes. This procedure does not, however, have any appreciable effect on the secondary proton dose shown in Fig. 5.



and NTC results are in reasonable agreement, while at large depths the LPSC and LPPC curves agree and are higher than the NTC curve. This general behavior is also exhibited by the three curves in Fig. 11. In Figs. 10 and 12 the secondary neutron dose in rem given by the LPSC code is in general somewhat higher than that given by NTC.

In Figs. 13-16 the total dose, i.e., the sum of the primary-proton, secondary-proton, and secondary-neutron doses, is shown. Figure 13 shows favorable agreement among the four codes, similar to the results presented in Fig. 1. This agreement, despite the large differences in the secondary-particle doses is, of course, due to the fact that the secondary-particle contribution to the total dose is small for the shield thicknesses considered here. The fact that the differences shown in Fig. 13 are for some depths even smaller than those shown in Fig. 1 is probably fortuitous. The large difference between the total dose given by LPPC and that given by the LPSC and NTC in Fig. 15 is due to the presumably erroneous secondary-proton dose calculated with the LPPC code.

In Figs. 14 and 16 the LPSC and NTC curves in rem are in reasonable agreement.

In general, the most consistent agreement is obtained between the results of the LPSC code and NTC. It is tempting to ascribe the difference in the results obtained with the two codes to the fact that LPSC employs the straightahead approximation, but some of this difference may arise from other sources such as differences in data.

#### ACKNOWLEDGMENTS

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67-5431

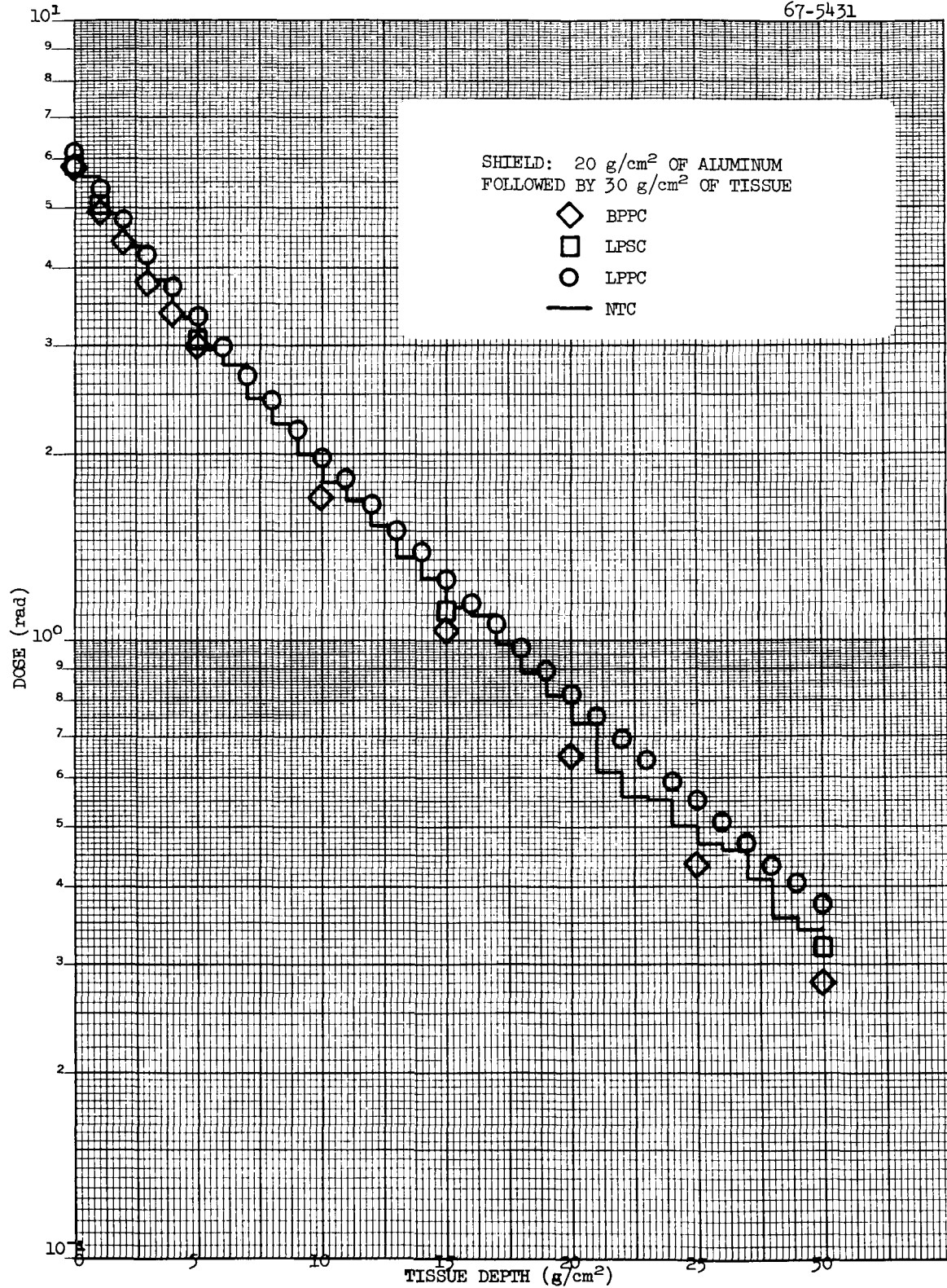


Fig. 1. Primary Proton Dose (rad) vs. Depth in Tissue.

67-5432

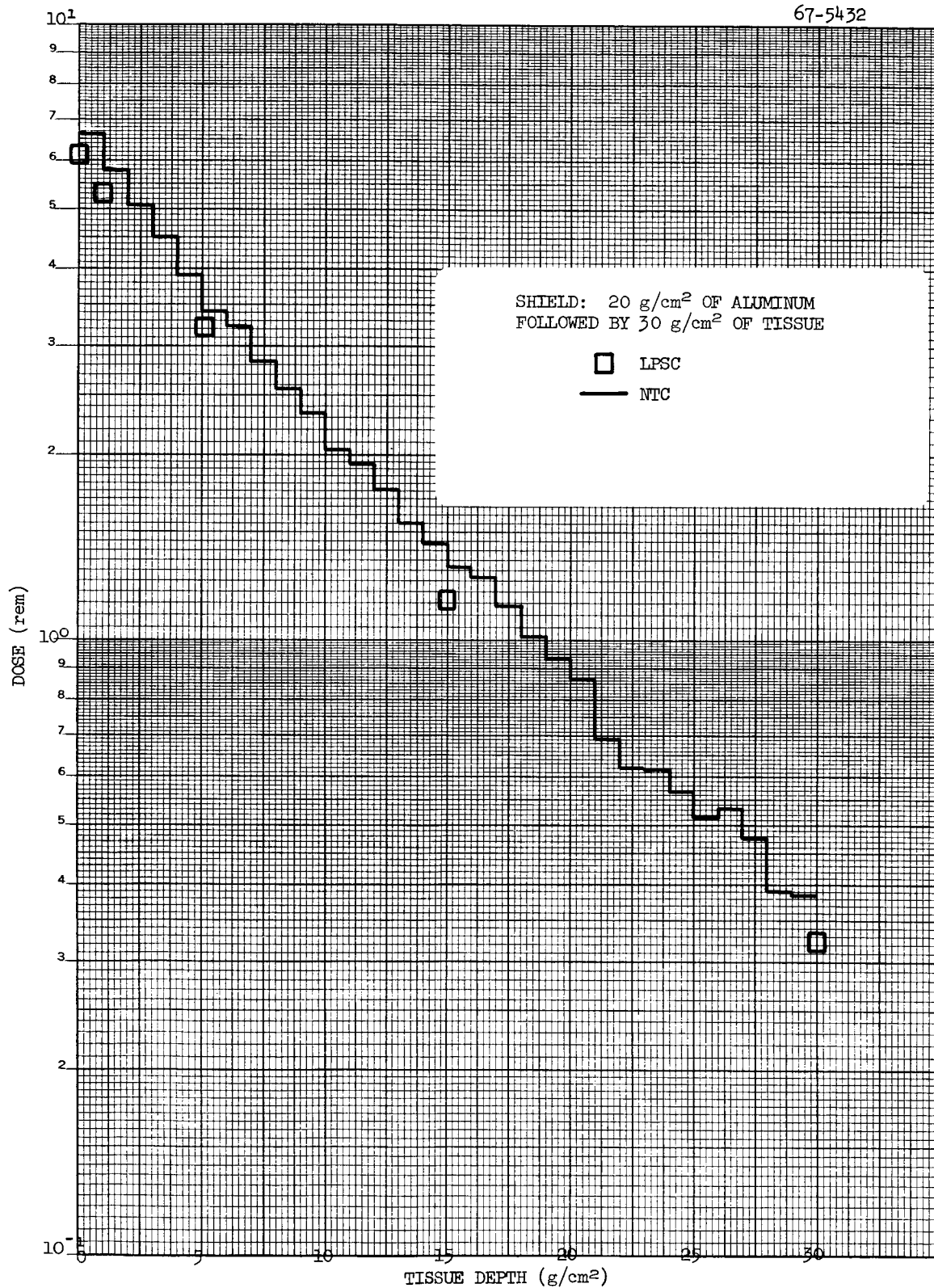


Fig. 2. Primary Proton Dose (rem) vs. Depth in Tissue.

67-5433

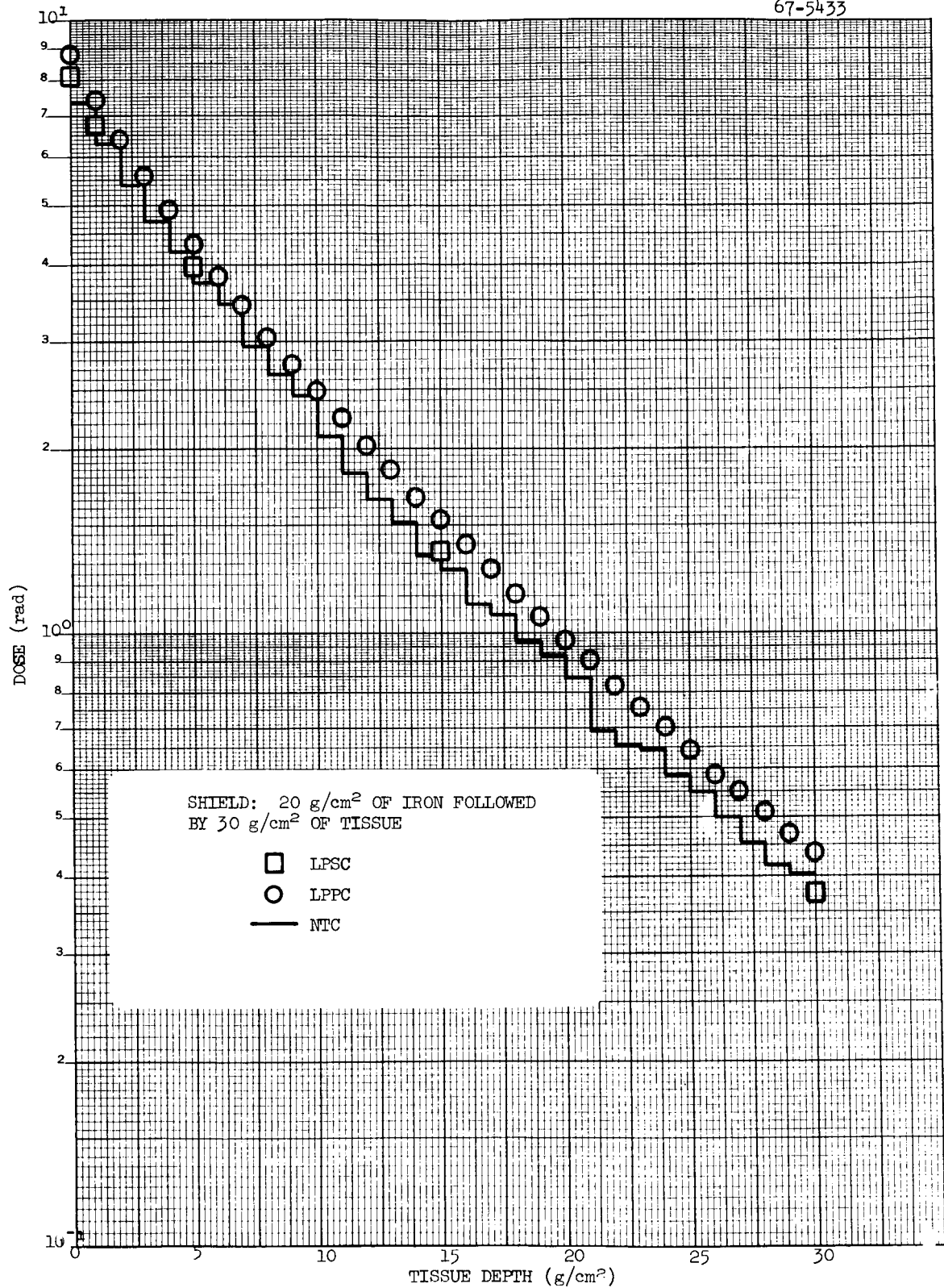


Fig. 3. Primary Proton Dose (rad) vs. Depth in Tissue.

67-5434

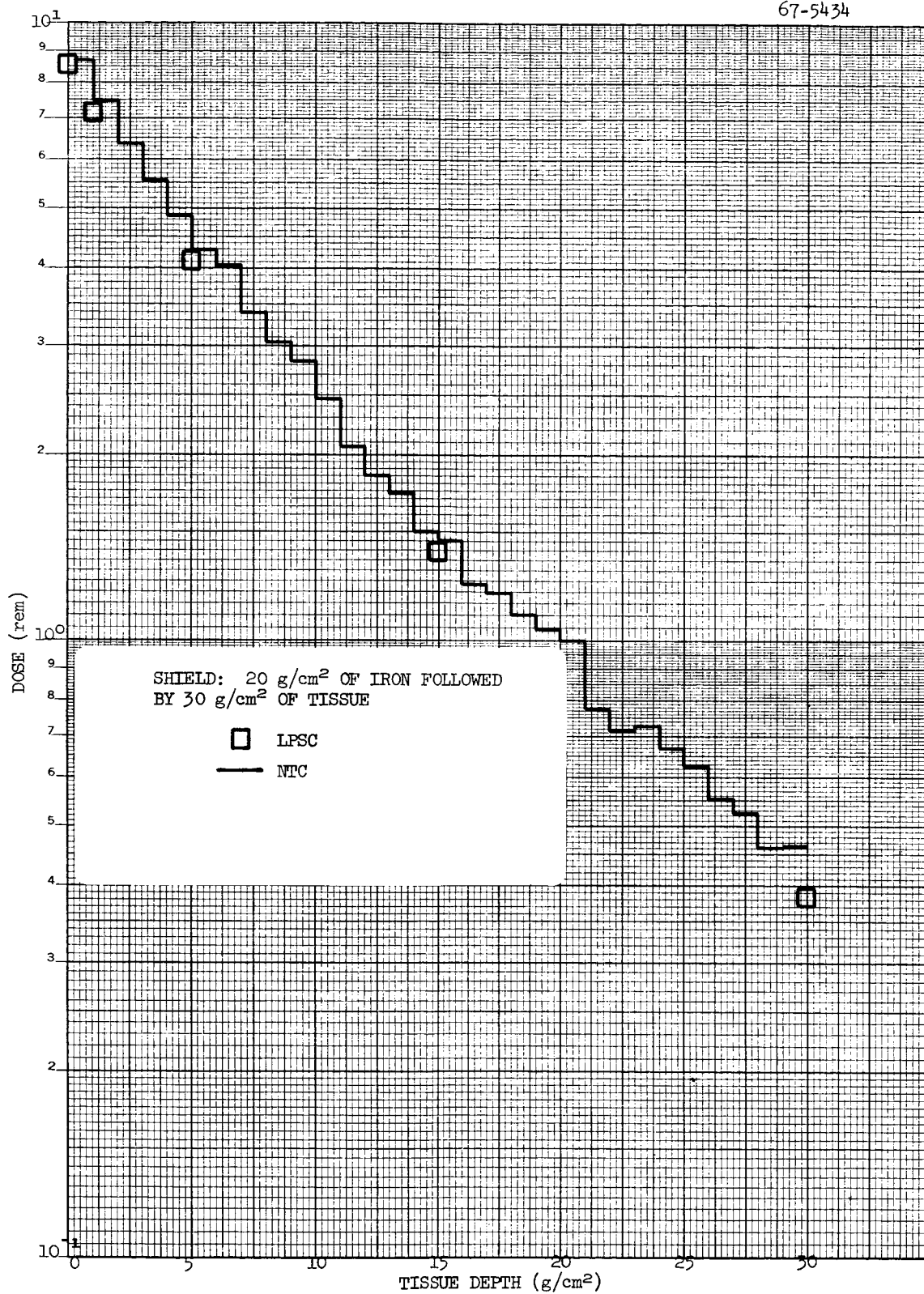


Fig. 4. Primary Proton Dose (rem) vs. Depth in Tissue.

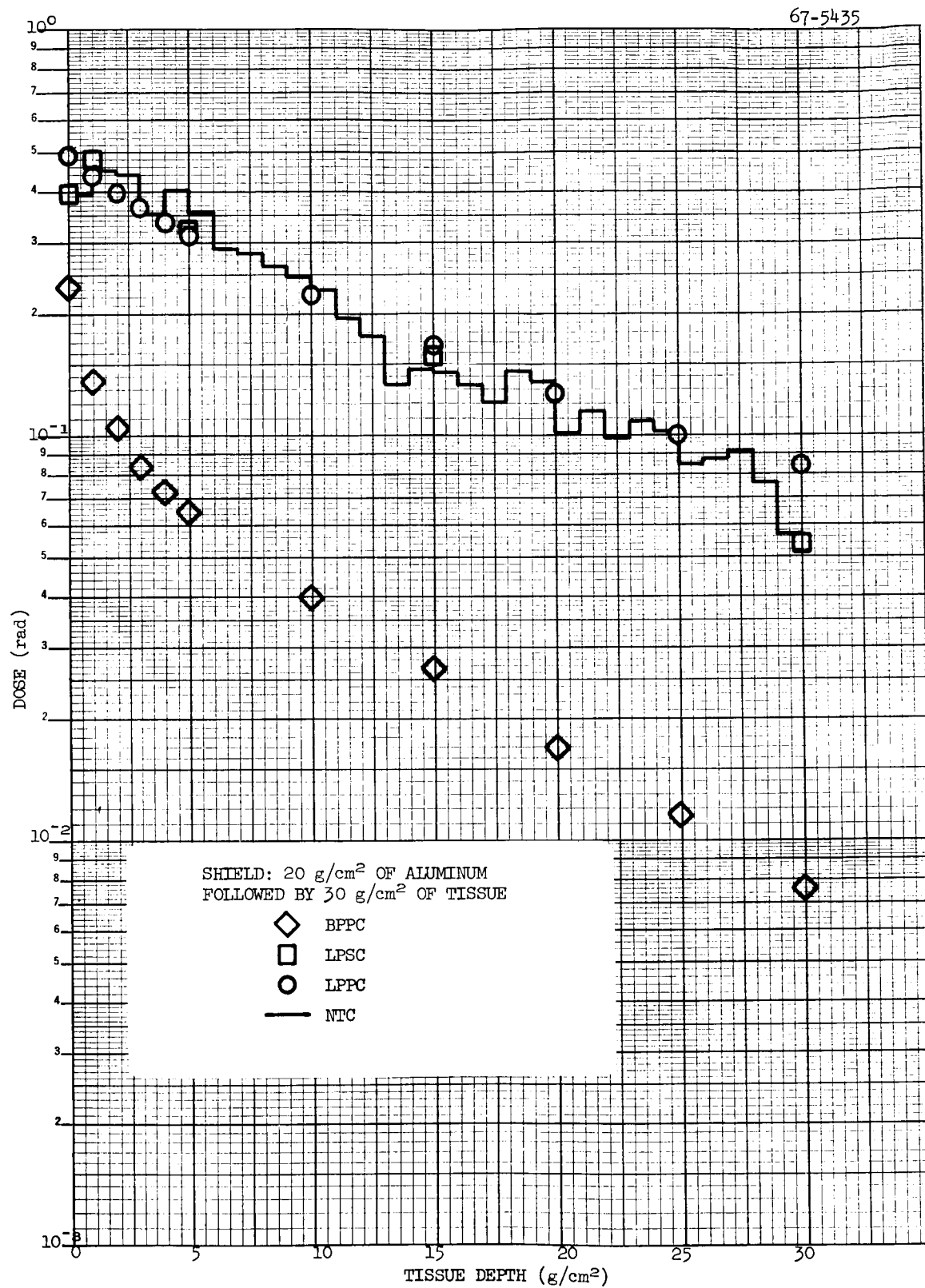


Fig. 5. Secondary Proton Dose (rad) vs. Depth in Tissue.

67-5436

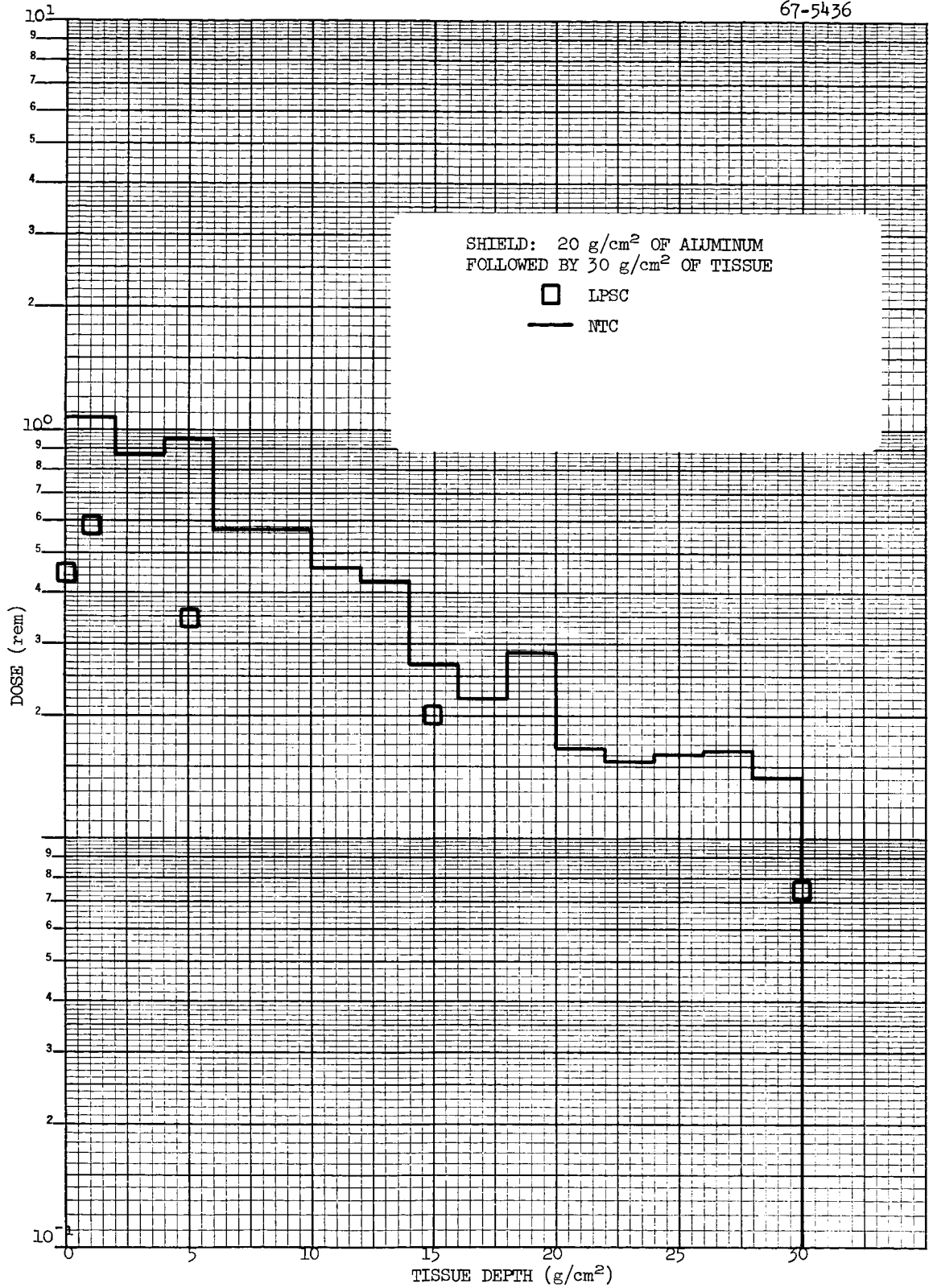


Fig. 6. Secondary Proton Dose (rem) vs. Depth in Tissue.



67-5437

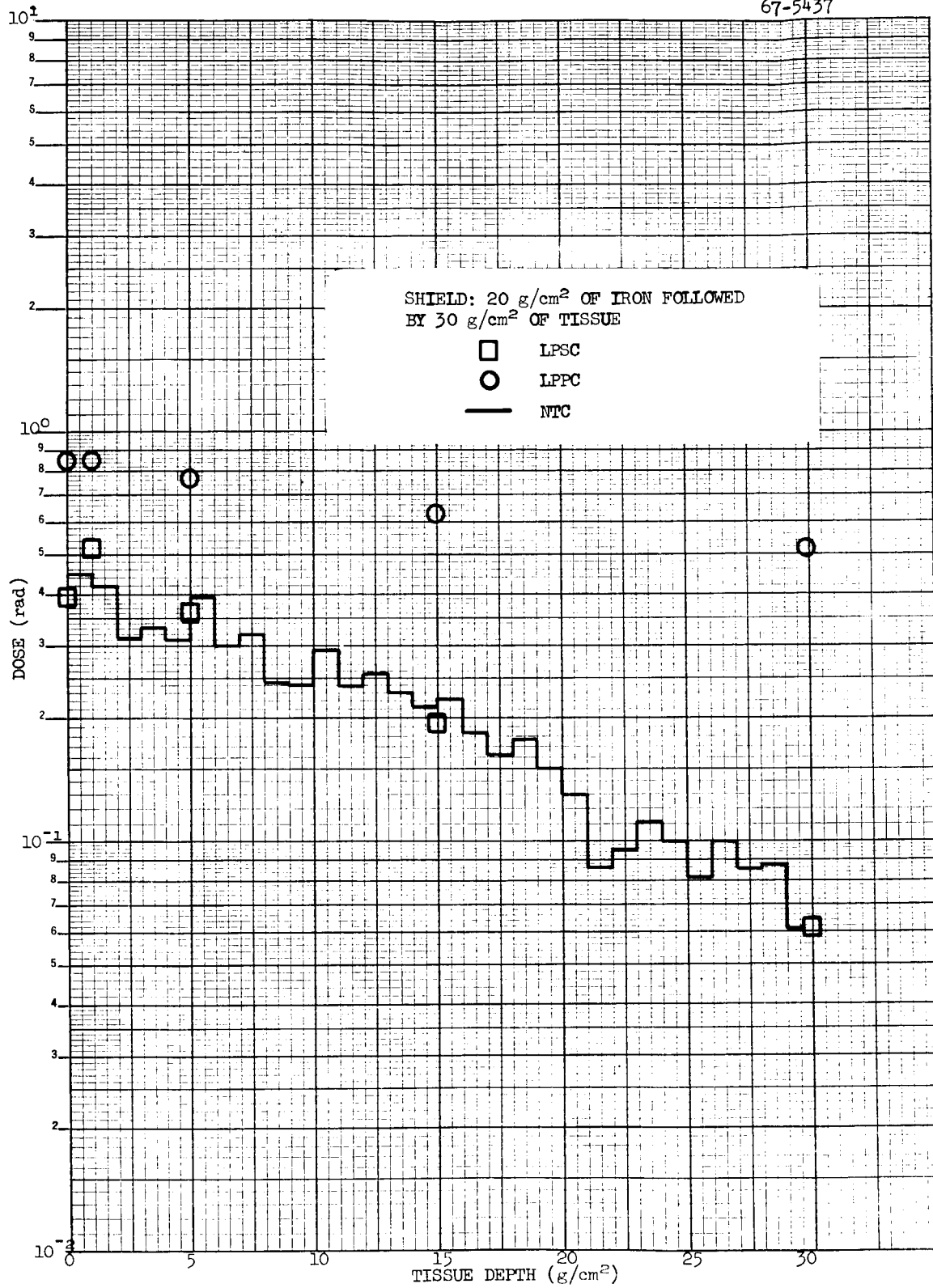


Fig. 7. Secondary Proton Dose (rad) vs. Depth in Tissue.

67-5438

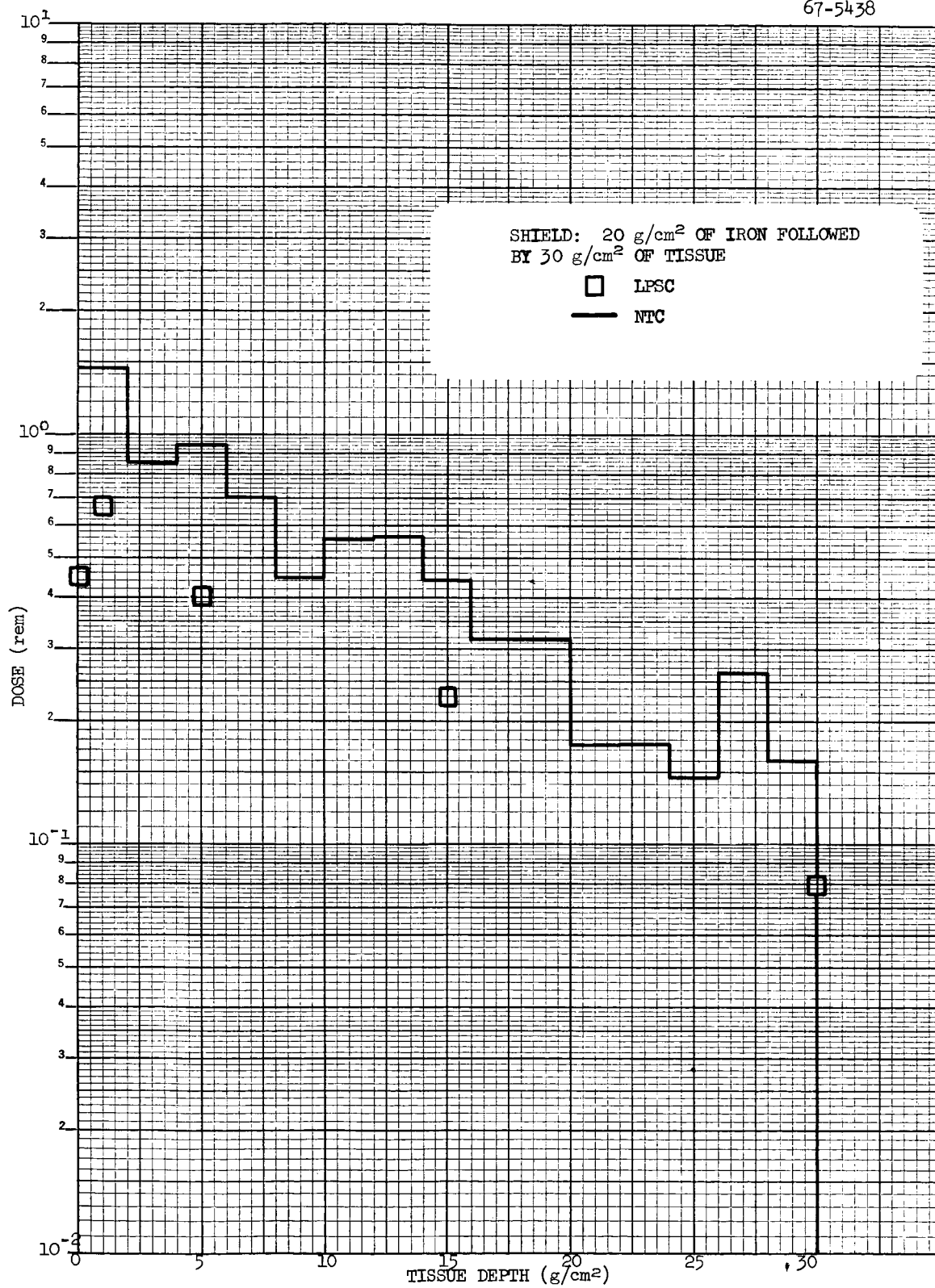


Fig. 8. Secondary Proton Dose (rem) vs. Depth in Tissue.

67-5439

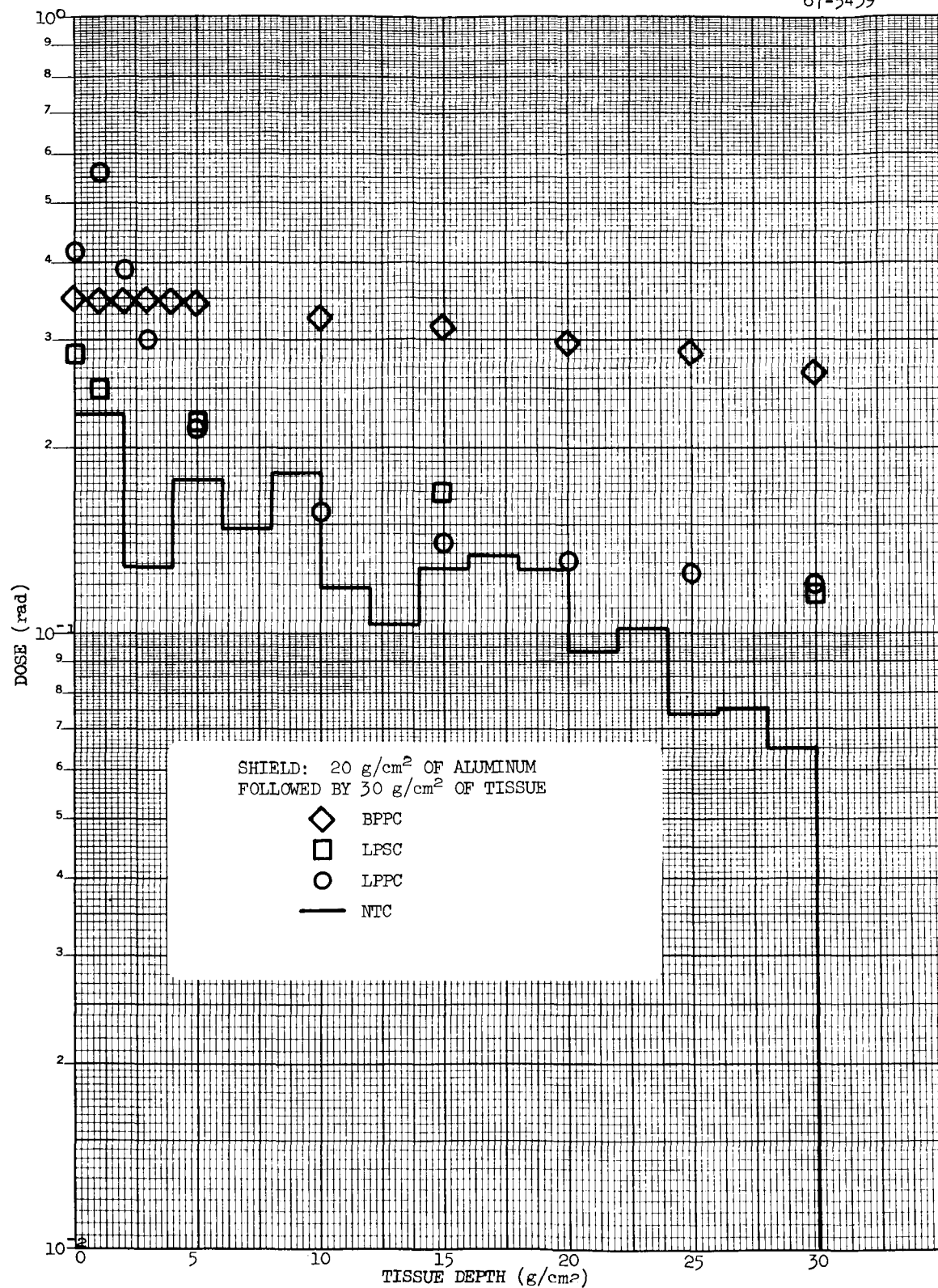


Fig. 9. Secondary Neutron Dose (rad) vs. Depth in Tissue.

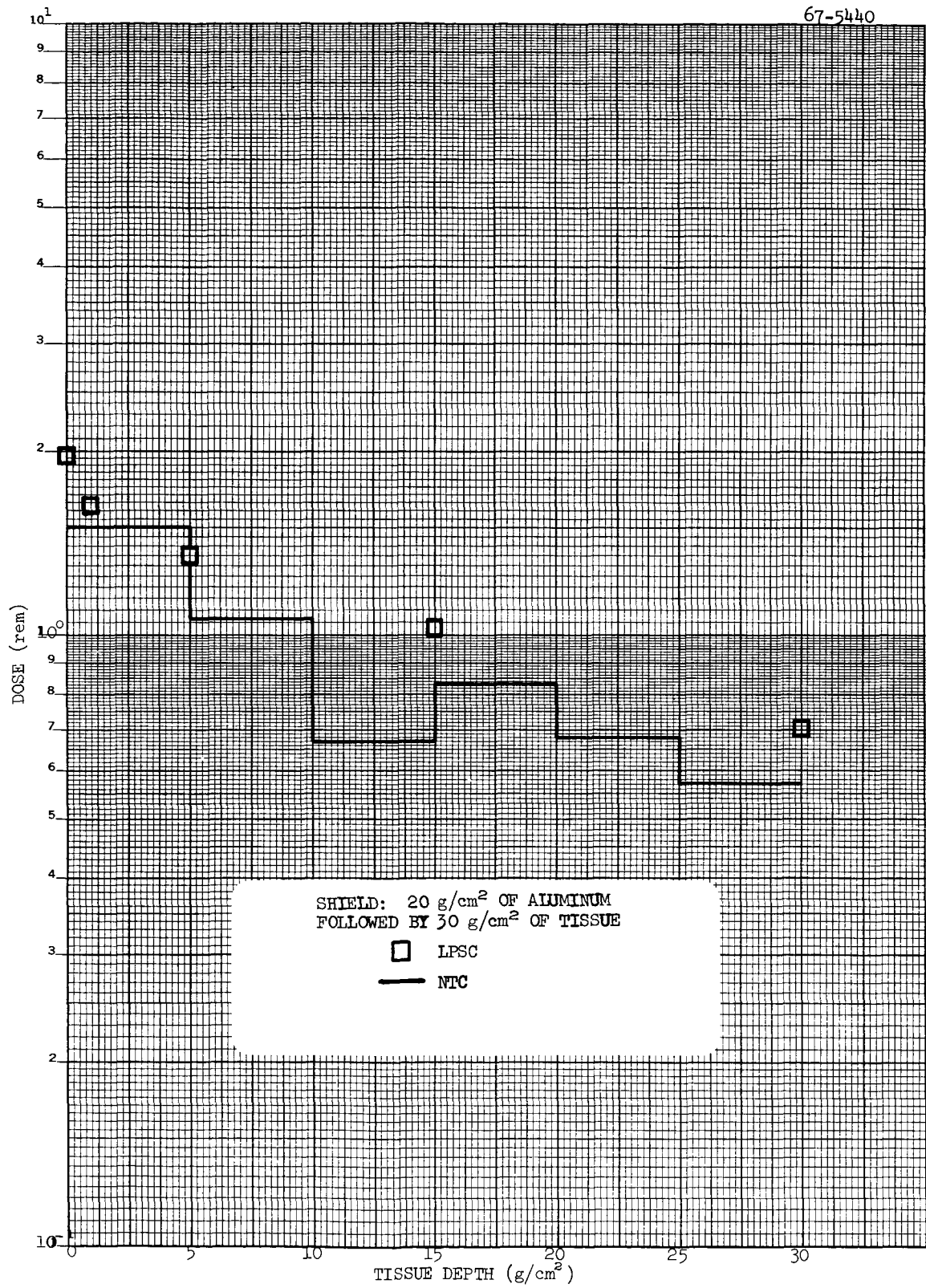


Fig. 10. Secondary Neutron Dose (rem) vs. Depth in Tissue.

67-5441

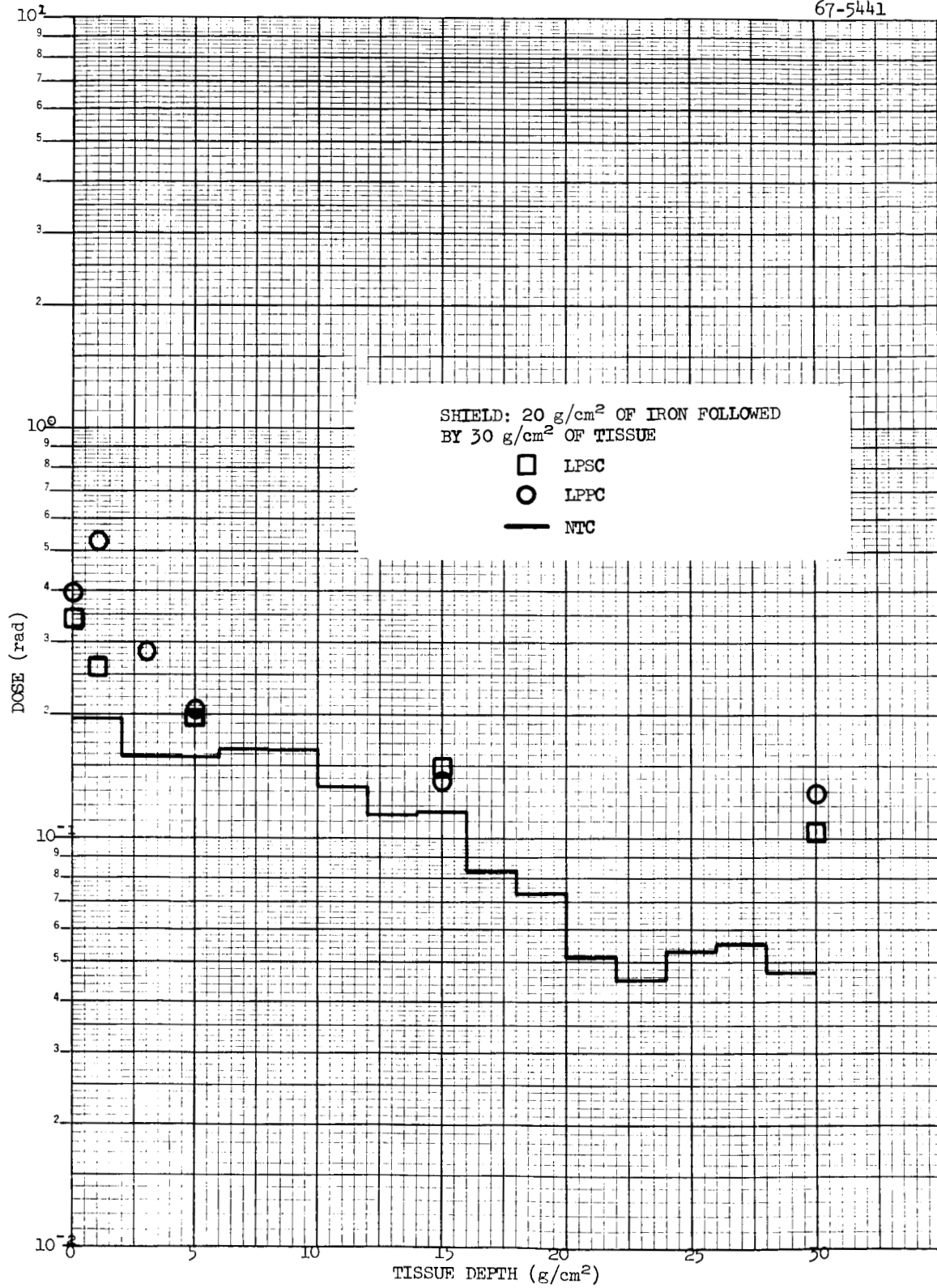


Fig. 11. Secondary Neutron Dose (rad) vs. Depth in Tissue.

67-5442

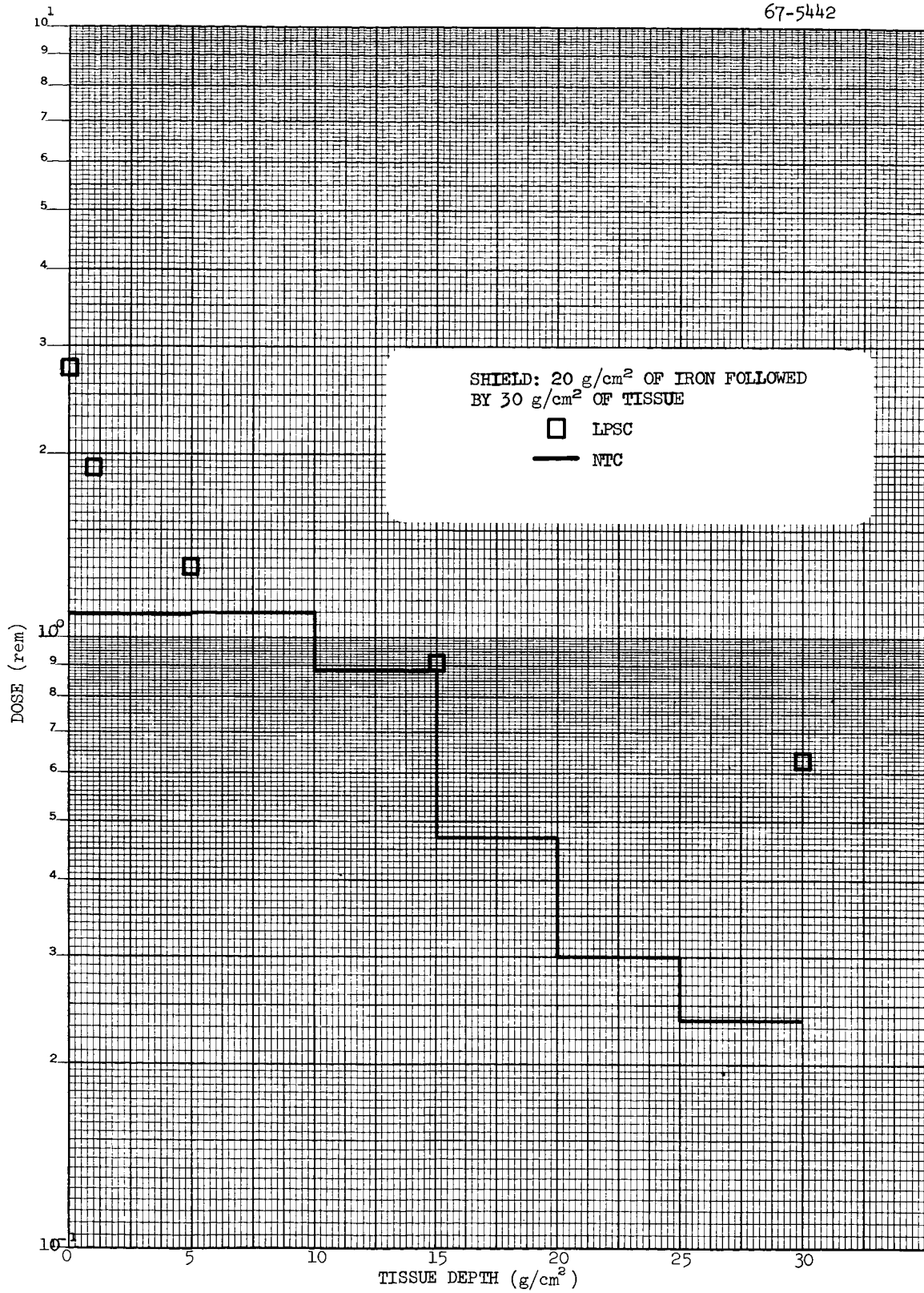


Fig. 12. Secondary Neutron Dose (rem) vs. Depth in Tissue.

67-5443

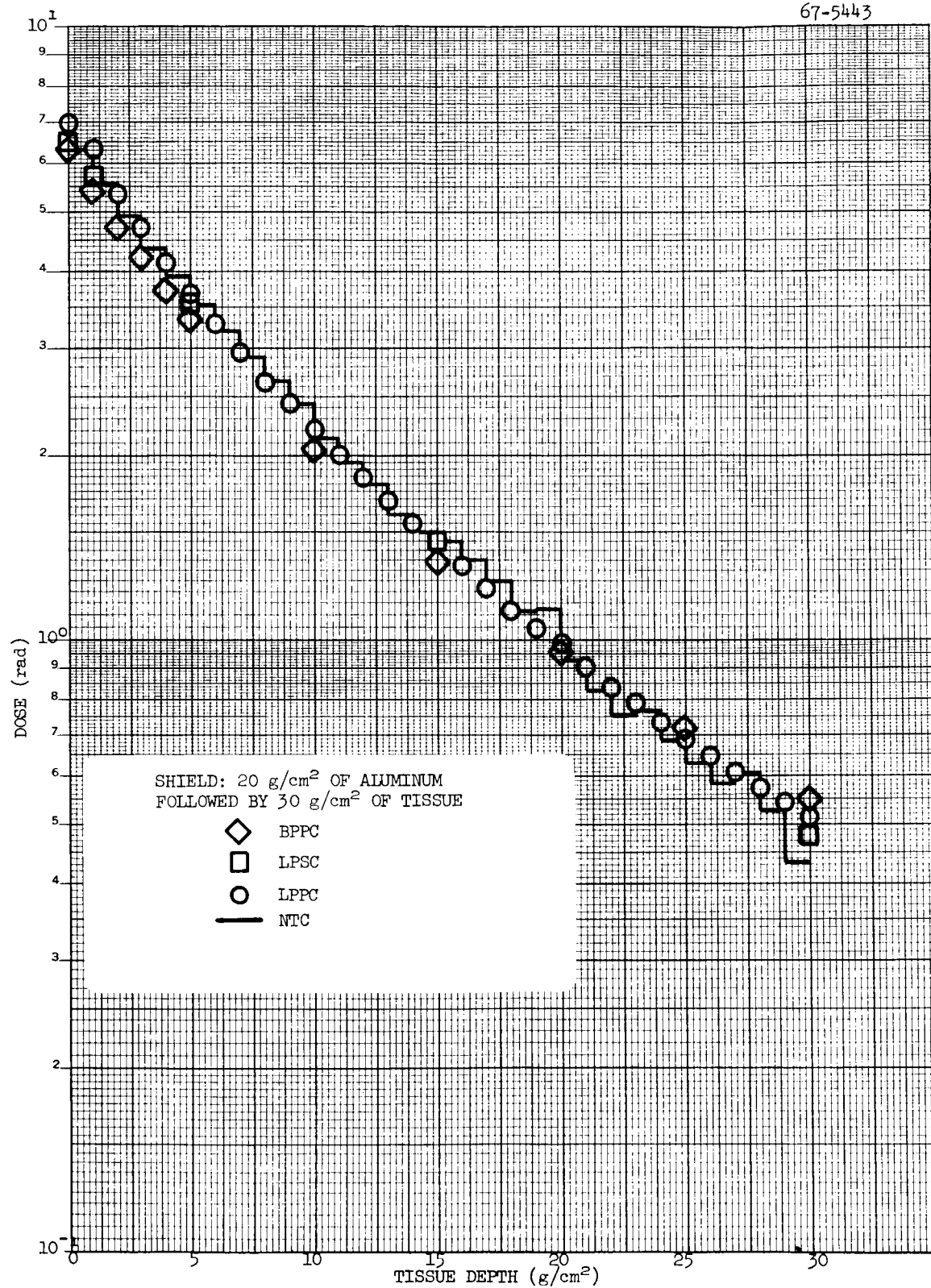


Fig. 13. Total Dose (rad) vs. Depth in Tissue.



67-5444

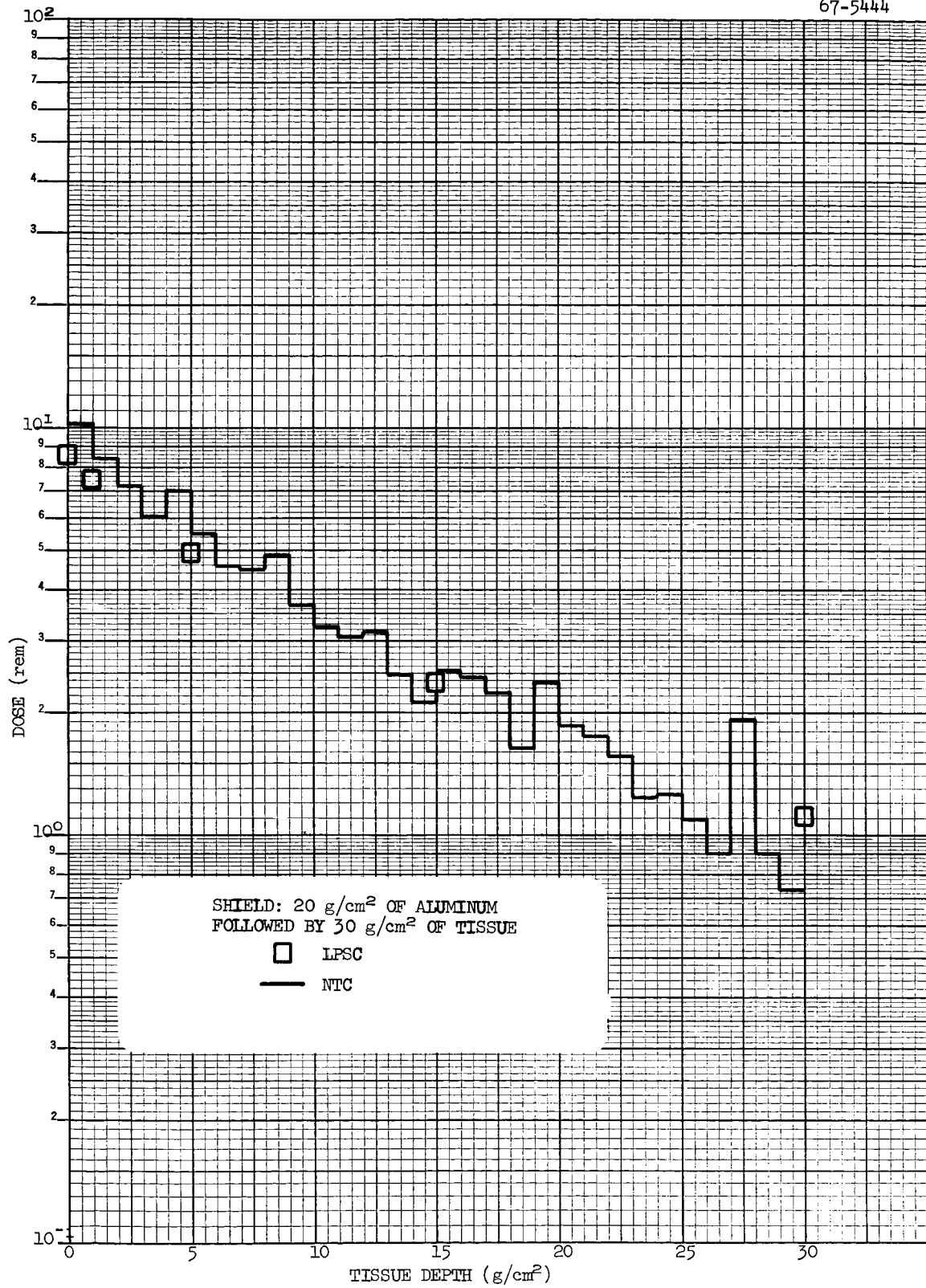


Fig. 14. Total Dose (rem) vs. Depth in Tissue.



67-5445

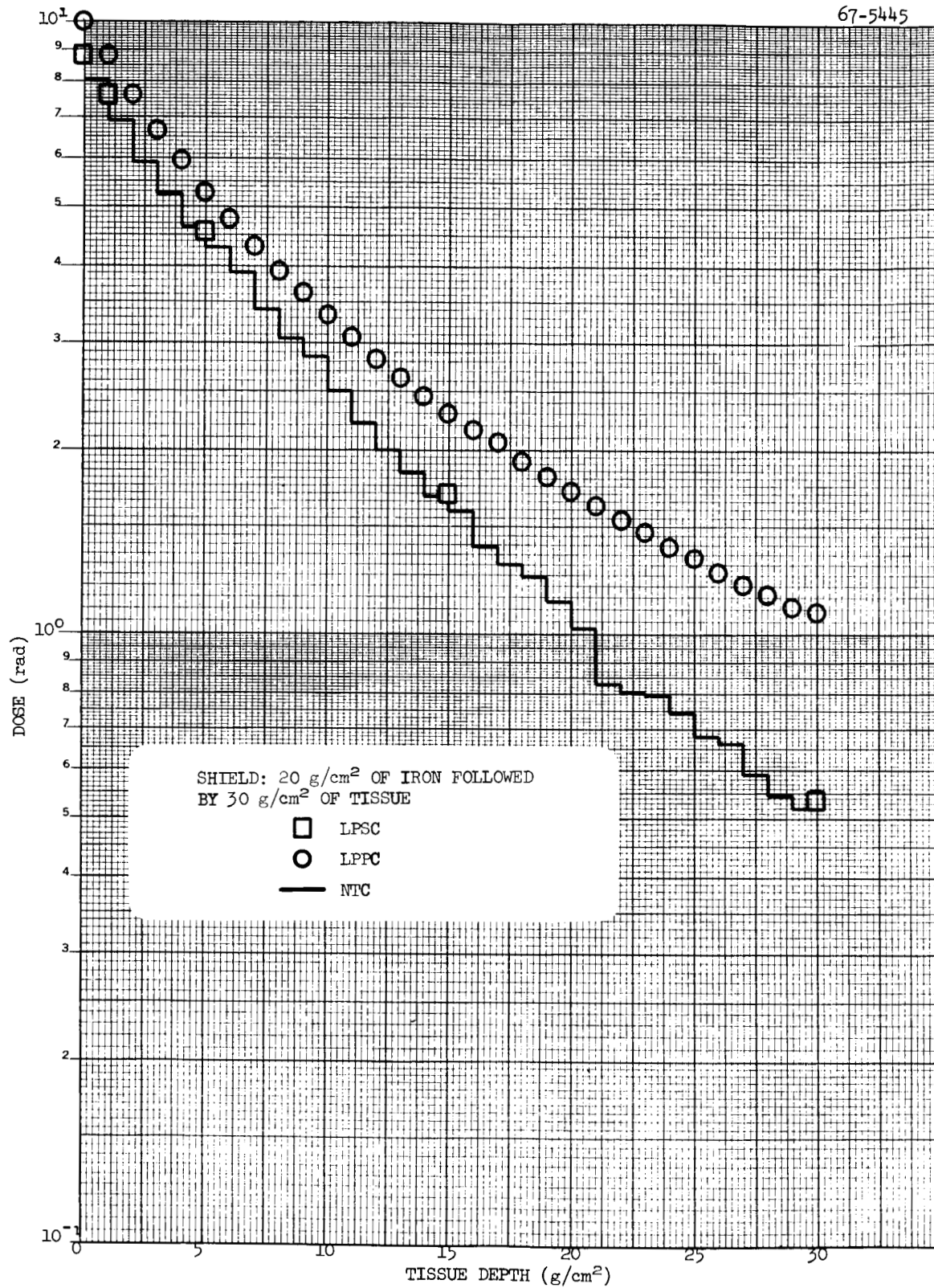


Fig. 15. Total Dose (rad) vs. Depth in Tissue.

67-5446

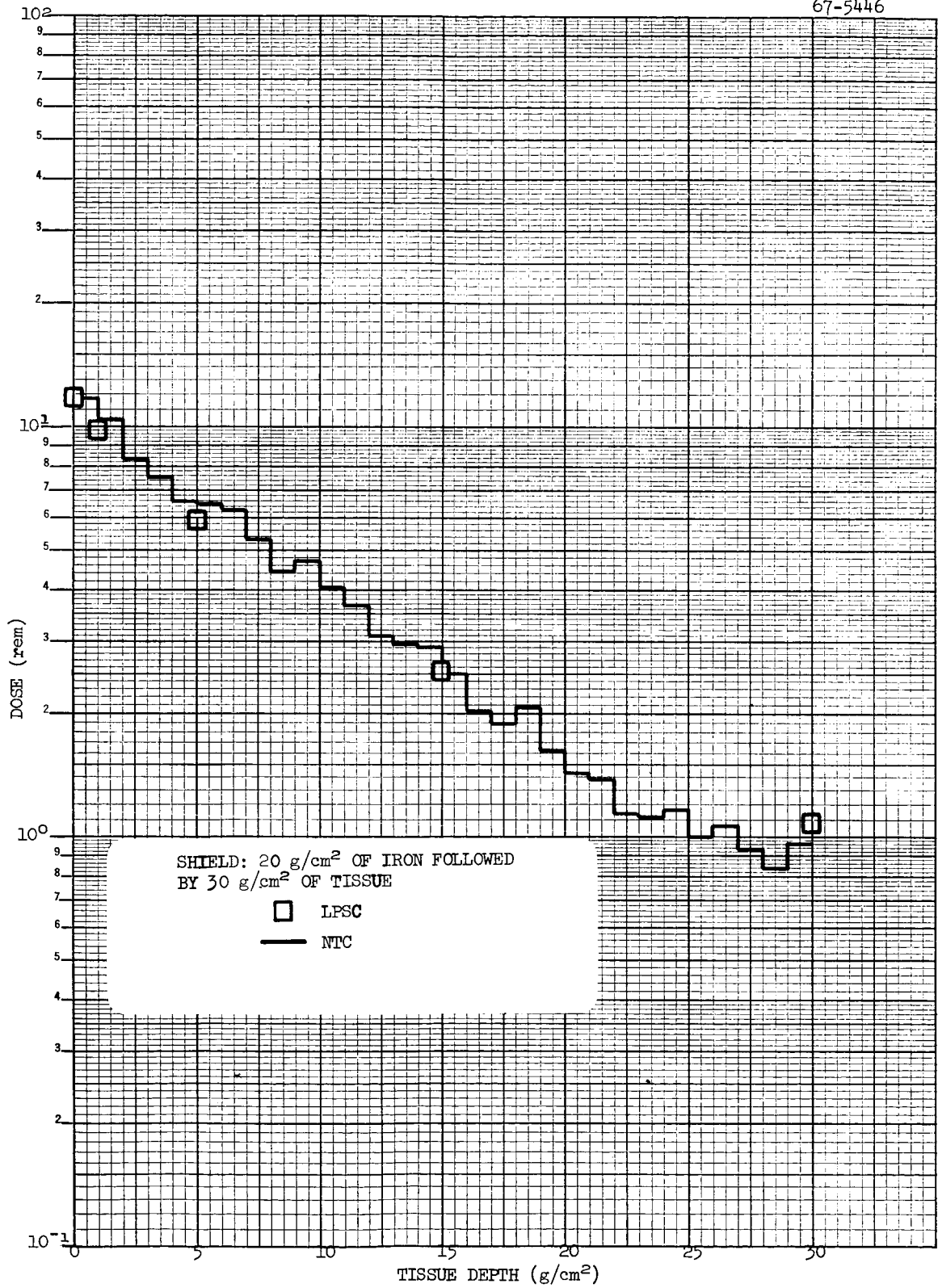


Fig. 16. Total Dose (rem) vs. Depth in Tissue.

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